

Virtual-Sparticle Threshold Effects on Large- E_T Jet Cross Sections

John Ellis

Theoretical Physics Division, CERN
1211 Geneva 23, Switzerland

and

Douglas A. Ross

Physics Department,
University of Southampton,
Southampton SO17 1BJ, United Kingdom

ABSTRACT

We discuss the one-loop virtual-sparticle corrections to QCD jet cross sections at large E_T and large dijet invariant masses, with reference to present Tevatron and future LHC collider experiments. We find characteristic peaks and dips in the sparticle threshold region, due to interferences with tree-level QCD diagrams. Their magnitudes may be several per cent of the parton subprocess cross sections, so they might provide a useful search tool that is complementary to the usual missing-energy signature for supersymmetry.

Recent data from the CDF collaboration on large- E_T hadronic jets [1] have stimulated interest in the possibility that jet measurements at hadronic colliders may be sensitive to quantum corrections due to virtual particles, such as those appearing in supersymmetric models [2, 3]. Hadron colliders such as the CERN $\bar{p}p$ collider, the Tevatron or the LHC are usually thought of as exploratory machines, with precision physics left to e^+e^- colliders such as LEP or the LHC. However, e^+e^- colliders are certainly also discovery machines, and the enormous event rates at present and future hadron colliders may provide precision tests of the Standard Model and its possible extensions. The interpretation of large- E_T jet cross sections inherits uncertainties from the non-perturbative parton distribution and fragmentation functions¹, but effects on the shape of the cross section in the neighbourhood of a new particle threshold may be discernible.

It is conceivable that precision jet measurements could provide a useful new way to detect sparticles indirectly. Even if they are being produced copiously, their decays may be difficult to disentangle, e.g., if they are dominated by cascades, or if R parity is violated. Thus, the mass reach in direct searches could well be less than the accessible range of E_T , as is now the case at the Tevatron, and could in the future also be the case at the LHC.

The one-loop quantum corrections to jet cross sections in the Standard Model have been calculated [8], and studied extensively [9]. First estimates of the one-loop virtual corrections in the minimal supersymmetric extension of the Standard Model have also been presented recently, including the ultraviolet logarithms associated with the slower running of the strong coupling α_s above the sparticle threshold [2], and sub-threshold effects [3]. However, a complete calculation which matches these contributions is not available, and the infrared logarithms associated with the separation between final states that do or do not contain sparticles have not been considered. In view of the physics interest mentioned in the previous paragraph, it is desirable to calculate exactly the one-loop sparticle effects from the threshold region on upwards.

In this paper, we present the main results of such a calculation, including self-energy, vertex and relevant aspects of “box” diagram contributions to the parton subprocesses $\bar{q}q \rightarrow \bar{q}q$, $qq \rightarrow qq$, $\bar{q}q \rightarrow gg$ and $qg \rightarrow qg$, which are expected to dominate large- E_T cross sections at the Tevatron and LHC. We present results which combine and match the behaviours below and above threshold, displaying them graphically as functions of the subprocess energy and centre-of-mass scattering angle. The numerical results we find are quite small, so that measurements with a statistical accuracy of the order of a percent in bins with widths of the order of 10% would be required to see effects in the E_T or dijet mass distribution. A more detailed presentation of our calculations, together with more discussion of their observability based on convolution with sample parton distribution functions, will be presented in a subsequent paper [10].

We work in the context of the Minimal Supersymmetric extension of the Standard Model (MSSM), assuming for simplicity that the squark partners of both the left- and right-handed helicity states $\tilde{q}_{L,R}$ of the five lightest quark flavours are degenerate with common mass m .

¹It has been suggested [5] that the apparent discrepancy reported by CDF [1] may be accommodated by these uncertainties, particularly in the gluon distribution: see however [6]. However, the CDF and D0 [4] data need to be reconciled before this issue can be resolved, after which one would know whether to entertain speculations about new physics [7], of which compositeness [1] is not the most conservative.

The gluino mass we denote by M . For simplicity, and to maximize the possible threshold effects, we assume equal masses for the squarks and gluinos, i.e. $m = M$. If the masses are very different, most of the higher-order contributions are suppressed below the higher-mass threshold. The effects of moderate mass differences between squarks and gluinos will be discussed in [10]. We consider radiative corrections to the scattering and production of gluons and the five lightest quark flavours, recognizing that $t\bar{t}$ production requires a separate treatment [11].

In this paper, we restrict our calculations to the contributions of self-energy insertions and vertex corrections shown in Fig. 1, which display the most dramatic behaviours in the threshold region. Previous experience with higher-order corrections indicates that contributions from “box” diagrams are likely to be small in the threshold region. Moreover, the results of ref. [3] indicate that the “box”-diagram contributions are significantly smaller than vertex and self-energy contributions, also at energies well below threshold. Nevertheless, the effects of these “boxes” will be included for completeness in ref. [10].

In order to match our higher-order calculation to a leading-order calculation in terms of a value of α_s extracted from data assuming the absence of sparticle loops, we use a renormalisation prescription in which the contributions for loops containing sparticles vanish in the low-momentum limit. In the case where the masses of the sparticles are all taken to be equal, this turns out to be equivalent to the \overline{MS} scheme with renormalisation mass scale μ set equal to the sparticle mass M ($= m$).

The fact that we perform a complete calculation extending from far below the sparticle threshold to very high energies provides us with several checks on the relative magnitudes and signs of the various diagrams shown in Fig. 1. In particular, the fact that the contribution to the β function from sparticle loops arises entirely from their contributions to the gluon self-energy provides us with the check that the non-abelian parts of the ultraviolet divergences of Figs 1(a) and 1(b) cancel against each other, and likewise Figs. 1(e) and 1(f). Moreover, for the same reason the ultraviolet divergence of Fig. 1(c) cancels against that of Fig 1(h), and likewise Fig 1(d) against 1(g). Furthermore, the abelian Ward-Takahashi identity tells us that the abelian part of the sum of the ultraviolet divergences in Figs 1(a) and 1(b) (and likewise Figs. 1(e) and 1(f)) cancel against the ultraviolet-divergent part of the fermion self energy of Fig. 1(i). We have also extracted the low-energy expansions $\propto q^2/m^2$ of our results, for comparison with [3]. Despite some minor differences, we confirm the general magnitude of the below-threshold corrections found in [3].

Our main results are shown in Fig. 2, in which we plot the one-loop virtual-sparticle correction to the subprocesses (a) $q_j \bar{q}_j \rightarrow q_k \bar{q}_k$, (b) $q \bar{q} \rightarrow g g$, and (c) $q g \rightarrow q g$, as functions of the square of the subprocess centre-of-mass energy, s . Full details of the results shown in these plots, as well as others, will be presented in [10]. In this letter, we focus your attention on the most important features of these plots, namely the distinctive peak and dip structures in the correction at the threshold $s = 4m^2$. These are consequences of the familiar discontinuity of the derivative of the real part of any amplitude at the branch point where the amplitude develops an imaginary part. Since the order α_s corrections are due to the interference between the tree and one-loop amplitudes, one cannot be sure that the effect will be positive. Indeed, the correction to the $q g \rightarrow q g$ subprocess shown in Fig. 2 (c) is negative.

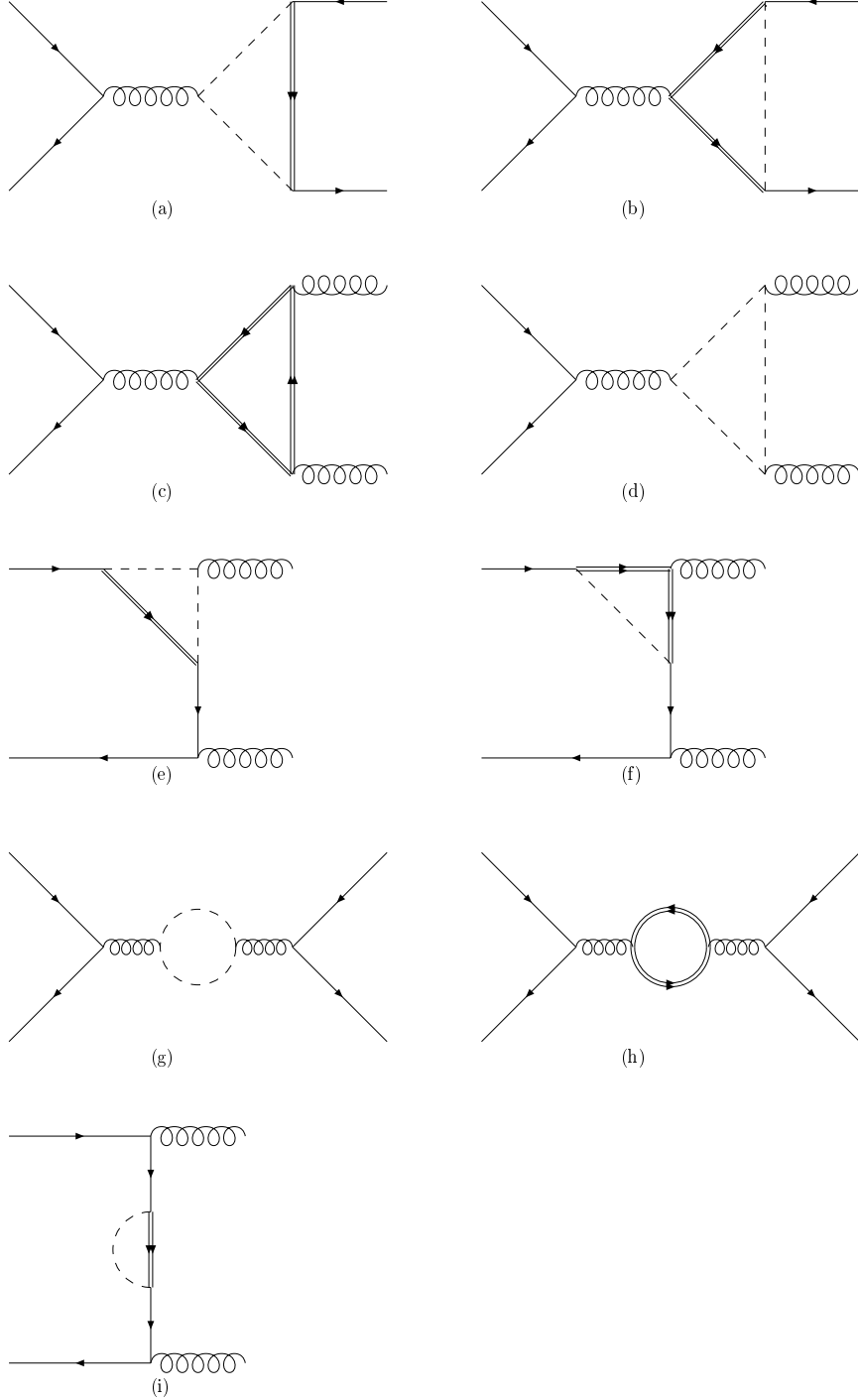


Figure 1: One-loop Feynman diagrams involving virtual sparticles in the MSSM for (a), (b) the $g\bar{q}q$ vertex in $q_i\bar{q}_i \rightarrow q_j\bar{q}_j$ scattering, (c), (d) the ggg vertex in $q\bar{q} \rightarrow gg$ scattering, (e), (f) the $g\bar{q}q$ vertex in $q\bar{q} \rightarrow gg$ scattering, (g), (h) the gluon self energy, and (i) the quark self energy. The broken lines represent squarks and the double solid lines represent gluinos.

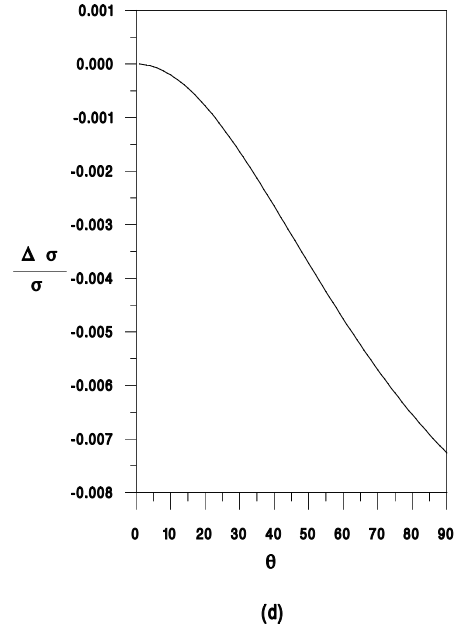
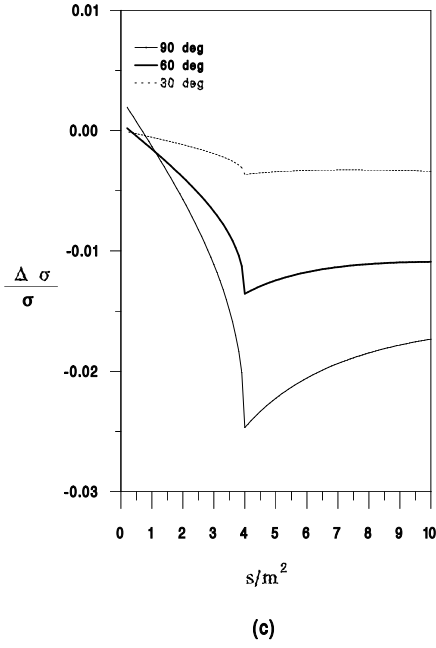
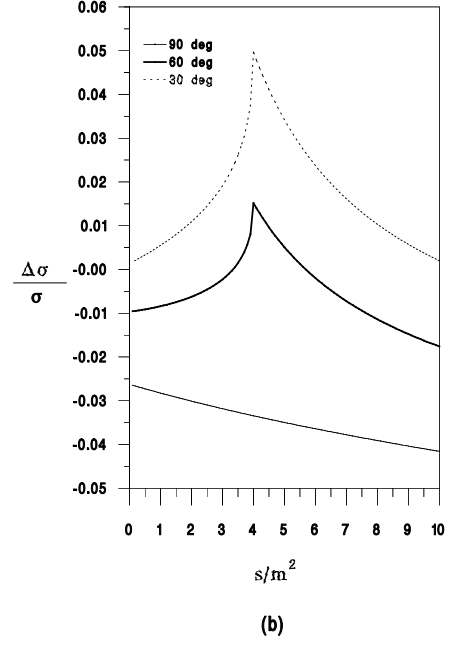
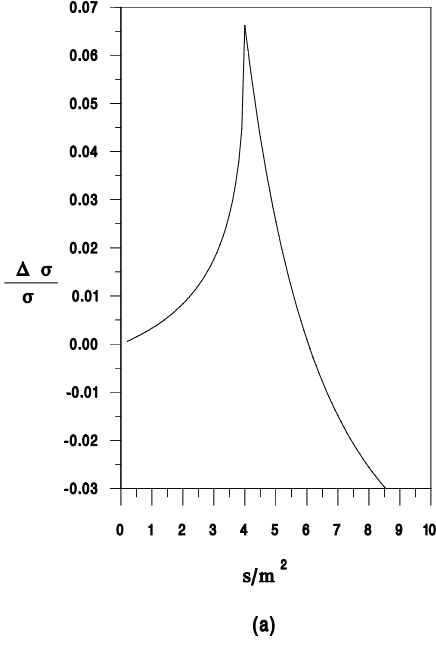


Figure 2: One-loop virtual-particle corrections in the threshold region of the subprocess centre-of-mass energy squared s to the processes (a) $q_j \bar{q}_j \rightarrow q_k \bar{q}_k$, (b) $q \bar{q} \rightarrow g g$ for three different subprocess centre-of-mass scattering angles, (c) $q g \rightarrow q g$ also for three different values of scattering angle, and (d) $q_j q_k \rightarrow q_j q_k$, against the centre-of-mass subprocess scattering angle, θ , for $s = 10m^2$. All corrections are evaluated using $\alpha_s = 0.11$.

The correction to the process $q\bar{q} \rightarrow q\bar{q}$ shown in Fig. 2(a) depends only on s , whereas the corrections to the other processes are also functions of the squared subprocess momentum transfer t . We have plotted in Figs. 2(b) and (c) the threshold behaviours at three different values of the centre-of-mass scattering angle. The fact that the threshold behaviour has a characteristic angular dependence means that it should be possible in principle to distinguish such virtual-particle threshold effects from other possible mechanisms for a structure in the dijet invariant mass, such as the production of a new particle with definite spin. Also shown in Fig. 2(d) are the one-loop corrections to the process $q_j q_k \rightarrow q_j q_k$, which is controlled by a gluon exchange in the t (or u) channel. Because of this, and because its direct-channel quantum numbers are exotic from the point of view of the MSSM, its corrections have no distinctive threshold behaviour in s . Therefore we have plotted it as a function of scattering angle for one large value of s ($= 10m^2$): we see that the corrections are negligible compared with those to the other subprocesses.

The one-loop virtual-particle corrections to the subprocess $q_i \bar{q}_j \rightarrow q_i \bar{q}_j$ are identical to those for $q_i q_j \rightarrow q_i q_j$. Since this cross-channel exchange reaction dominates over $q_i \bar{q}_i$ annihilation, the threshold effect shown in Fig. 2 (a) will be strongly diluted if one studies the dijet mass distribution without any flavour separation. We have also calculated virtual-particle threshold effects in the subprocess $gg \rightarrow gg$, but do not display the results here, as elastic gg scattering is relatively significant only at low values of the dijet mass, below those of interest at the Tevatron. We find for this subprocess a substantial threshold enhancement comparable in size and width to that in Fig. 2 (a) [10].

Knowledge of the threshold structures in Figs. 2 (a),(b),(c) supplements the corrections in the low-energy limit $s \ll m^2$ calculated in [3]. There it was estimated that internal sparticle effects are likely to be of order 1%, and we find here that corrections as large as 5-6 % can be obtained in some subprocesses, albeit in a narrow energy region around the threshold.

The suggestion [2] that the effects of internal sparticle loops can be estimated from their effect on the running of the coupling must also be treated with caution. In the first place, the running of the coupling only gives information about leading logarithms, which would dominate the corrections only at energies far above the threshold, and *cannot* be used to estimate the correction in the threshold region². Furthermore, one can only extract leading logarithms from the behaviour of the running of the coupling for totally inclusive processes. More precisely, the leading logarithms can be obtained from the running of the coupling only for infrared-safe processes in which there are no other relevant mass scales. In the case under consideration, there are contributions which would give rise to collinear divergences in the limit where the particle masses were taken to be zero. Such divergences would normally be cancelled by the emission of real collinear sparticles if these were indistinguishable from final states containing final state sparticles. In the real world, however, the emission of massive particles would have a clear missing-energy (if R parity is conserved) or multi-jet/lepton (if R parity is not conserved) signal. Therefore it is possible to distinguish clearly between the real and virtual particle corrections, each of which has (equal and opposite) large logarithms in the high-energy limit, over and above those extracted from the running of the coupling.

²At energies sufficiently far above threshold, one should also take into account sparticle effects on the evolution of the parton structure functions, but this effect is not relevant in the threshold region that we study here.

These logarithms only dominate the corrections to the cross-sections at energies much larger than those displayed in Fig. 2. In fact we have checked numerically that they only set in for values of s greater than $1000m^2$ in the case of quark production and $s > 100m^2$ for gluon production.

The structures shown in Figs. 2 (a),(b),(c) are rather sharp. In order to determine their effect on the E_T cross-sections, it is necessary to perform a convolution of the cross section for each subprocess with the corresponding parton distribution functions [9]. We defer a full discussion of this to ref.[10], but it is clear that there will be some structure in the E_T distribution around $E_T = m$ analogous to that at $M_W/2$ in the charged-lepton energy spectrum in $W \rightarrow \ell \nu$ decay. Quantification of this effect requires a convolution of the subprocess cross sections calculated here with the appropriate parton distributions, which is beyond the scope of this work. However, jet E_T distributions are probably not ideal quantities for observing this particular signal for supersymmetry.

It would be preferable to study experimentally the distribution in the dijet mass M_X , which would exhibit directly the threshold structure at $M_X = 2m$. Since the fractional experimental resolution in this quantity improves at higher energies, it may be possible for measurements at the LHC to achieve a resolution which is comparable with the widths of the peaks shown in Fig. 2. It appears possible that the LHC experiments might be able to achieve a resolution in the dijet invariant mass of around 10 %. This is comparable to the widths of the peaks shown in Fig. 2. We do not address here the convolution of the parton subprocesses we calculate with realistic parton distributions relevant to the Tevatron and LHC experiments. However, their dijet mass resolutions might be sufficient to offer the possibility of observing an abrupt increase (or decrease) in a subprocess differential cross-section with respect to M_X at $M_X = m$, which could be a very clean signal for the sparticle threshold. If it could be measured, the magnitude of the effect - which is expected to be of the order of 5 % according to the calculation reported here - would be a valuable check that the new threshold was due to supersymmetry, with the correct dynamics and magnitudes for the couplings of sparticles to each other and to quarks and gluons.

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